PAVEMENT DESIGN CONSIDERATIONS REGARDING THE INTRODUCTION OF THE A380

By:
Kars P. Drenth
Netherlands Pavement Consultants
PO Box 2756, 3500 GT UTRECHT
The Netherlands

PRESENTED FOR THE 2002 FEDERAL AVIATION ADMINISTRATION AIRPORT TECHNOLOGY TRANSFER CONFERENCE

05/02

Abstract

To cope with the increasing traffic congestion and predicted growth the use of larger aircraft can be part of a solution. The demand for these large aircraft made the manufacturer Airbus decide to start the production of the New Large Aircraft (NLA) generation, the A380. To be prepared for these larger and heavier aircraft, the so-called NLA has been introduced into the predicted fleet-mix for the design of the new 5th runway of Amsterdam Airport Schiphol (AAS), being operational late 2002. In comparison to the ‘standard’ design consisting of 200 mm polymer modified asphalt (PMA), 700 mm cement treated base (CTB) and 500 mm sand subbase on a subgrade with CBR 3%, an alternative pavement composition has been proposed. The objective of this alternative pavement structure is to avoid the drawbacks of the ‘standard ‘ design, being the sensitivity of the CTB for overloading and/or an increase in future aircraft weights in the first place and secondly the precautions needed to cope with reflective cracking. The choice of an asphalt surfacing is based on its tolerance in combination with soft subsoil conditions and the speed of maintenance measures.

The alternative pavement structure is based on the fact that the critical design factor should be placed as high as possible in the pavement structure to make future corrective structural measures more easily. In this case the critical location, the horizontal stress at the bottom of the CTB of the ‘standard’ design, is moved to the bottom of the asphalt layer (horizontal strain) in the alternative design. This is made possible by using a 500 mm thick cement bound subbase layer on top of the soft subgrade and intermediate 500 mm thick sand layer as load spreading intermediary. To avoid the sensitivity of the pavement structure for any reflective cracking, a 200 mm thick unbound aggregate base layer is placed on top of the cement bound subbase. The surface of the runway pavement has a thickness of 250 mm, being a combination of an asphalt wearing and binding course together with an asphalt base layer.

In the structural design of the alternative pavement composition use is made of the APSDS (Airport Pavement Structural Design System) software package utilizing the Cumulative Damage Factor (CDF) approach. The results are compared with LEDFAA (Layered Elastic Design Federal Aviation Administration) output. A thorough analysis has been made regarding the reliability of the design, together with the material characteristics to be used and the deformation resistance of the unbound aggregate interlayer. Based on these calculations the alternative design is structurally sound and allows a planned approach towards structural maintenance, reducing the overall need as well as the costs. Although AAS did at the end choose the ‘standard’ design for the 5th runway, the proposed alternative was adopted for the reconstruction of Taxiway Alpha A8-9.

Introduction

Airport pavements have seen a fast increase in frequency and weight of aircraft due to a growth in number of passengers. To cope with such a growth aircraft manufacturer design new aircraft types capable of transporting more passengers. This results in an increase in gross weight of the new aircraft types. An increase in the number of tires and landing gears is used to restrict the maximum load per wheel, which resulted in the dual-tridem gear lay-out of the B777 and the use of tridem gears for the Airbus A380. The international accepted design methods of ICAO [1] and FAA [2,3] have not been able to keep pace with this tendency in aircraft design. A discussion regarding this problem was started based on the ACN (Aircraft Classification Number) to be assigned to the B777. The core of this discussion is attributed to the lack of knowledge of the interaction between six wheels in one single landing gear. The construction of the National Airport Pavement Test Facility (NAPTF) in Atlantic City is based on the need for developing new design procedures for the new B777 and A380 type of aircraft.

In the mean time however the construction of new airport pavements such as new runways has to continue, although the predicted fleet-mix does include the new generation large aircraft. Environmental issues regarding noise reduction give cause for the need of extra runways. The uncertainty regarding the stresses developed in the pavement structure and the uncertainty in structural pavement life has been the motive to look for alternative pavement structures less sensitive to the combined stresses of multi-wheel landing gears. Alternative pavements in this case are those structures needing only relatively inexpensive corrective measures to increase the structural capacity in case of an underestimated traffic prediction or increase in frequency or weight of the NLA generation of aircraft types.

Design considerations

At the location of the new 5th runway the subsoil conditions in general vary but an average CBR-value of 3% has been adopted. Several pavement types, such as asphalt concrete (AC), unreinforced concrete slabs (PCC) and continuously reinforced concrete pavements (CRCP) have been considered. However, due to the presence of the soft compressible clay layers an AC pavement structure was given preference, especially regarding the ease and speed of future maintenance activities.

The structural design of the 'standard' pavement construction for the 5th runway of AAS, being a 200 mm PMA on top of 700 mm CTB and 500 mm thick sand layer, is based on the reflective cracking criterion and secondly on primary deformation (rutting). The CTB layer in this case is the by AAS adopted standard recycled mix of 60% concrete and 40% milled asphalt rubble. Secondary deformation should at all times be avoided and therefore the vertical subgrade strain should not be the failure mode that will govern the design. The drawback of a thick bound base layer in combination with a soft subsoil (with intermediate 500 mm thick sand layer) is its structural sensitivity for the horizontal tensile stresses at the bottom of this layer. This stress level is defined by the variation in subsoil strength, the variation of the mechanical parameters of the CTB and the aircraft loading. A pre-analysis showed that the design life of this type of pavement structure is extremely sensitive for a variation in allowable flexural tensile strength of the CTB material. The use of more cement to increase its strength does make this material more sensitive for cracking due to shrinkage or temperature variations. This in turn will create the need for an asphalt mix having better characteristics regarding reflective cracking. Either making the CTB layer thicker than required or using in the design a lower strength based on a cracked layer can increase the safety factor. However, like all cement bound materials, structural cracking can be introduced by one single heavy load. This unwanted situation is likely to be introduced by the new multiple-wheel gear layouts. As the development of even larger aircraft models of existing types can not be ruled out, the need for pavement structures less sensitive for overloading and easier to adjust in a most economical way is desirable. This wish has led to the development of an alternative pavement structure for the new runway of AAS designed for a fleet-mix containing NLA/A380 type of aircraft.

The alternative pavement design [4] is based on a combination of improving the subsoil conditions and using a stress distributing bound subbase layer. To reduce possible differential settlements the subgrade at the location of the 5th runway will be improved by 'pre-loading' using a new technique based on vacuum consolidation. The pre-loading is achieved by sealing off the soil at the top by a membrane and pumping water out of the soft layers from a depth of about seven meters using a grid of vertical drainage channels. Further elaboration on this special technique is outside the scope of this paper.

To avoid reflective cracking a high quality unbound aggregate interlayer is introduced between the bound subbase, and asphalt concrete base and surface layers. As planned maintenance is growing in importance for optimal use of all available runways, the likelihood of unpredicted localized distresses caused through the use of a thick bound base layer will be minimized using the alternative pavement design.

Design inputs

The aircraft loading is one of the fundamental inputs for a structural analysis of the pavement structure required. The future traffic-mix for runway 18-36 (5th runway) is expressed in take-off and landing numbers of the design aircraft per aircraft category. The division into categories is mainly based on the wingspan and is presented in Table 1.

Table 1. Aircraft movements 30 year design period

Cat	**Type**	**2001-2015**		**2016-2030**		**2001-2030**	
		Take-off	Landing	Take-off	Landing	Take-off	Landing
1	Saab 340	41,850	52,500	0	0	41,850	52,500
2	Fokker 50	176,102	228,000	197,625	255,000	373,727	483,000
3	Fokker 100	358,914	468,000	495,225	639,000	854,139	1,107,000
4	Airbus A320	363,630	471,000	413,850	534,000	777,480	1,005,000
5	Boeing 767-300	198,422	259,500	295,275	381,000	493,697	640,500
6A	Boeing 747-300	11,957	15,000	0	0	11,957	15,000
6B	Boeing 747-400	84,099	109,500	111,600	144,000	195,699	253,500
6C	MD 11	53,143	69,000	65,100	84,000	118,243	153,000
6'	Boeing 777-300	30,756	40,500	53,475	69,000	84,231	109,500
6D	NLA (A380)	10,164	13,500	20,925	27,000	31,089	40,500

The structural design inputs are used to calculate the stresses and strains in the materials used in all the different layers. Based on the fatigue models for the different material types and the response calculated the pavement structure will be tuned to the design life required. For a standard mechanistic analytical approach the performance relationships used are:

- asphalt concrete: $N = [1497/\mu e_t]^{5.244}$ [5] (1)

- CTB subbase: $\log(N) = 11.782-12.121*s_t/f_t$ [6] (2)

- subgrade: $N = [3300/\mu e_v]^{8.92}$ [7] (3)

where:

N	= number of allowable load repetitions
μe_t	= horizontal tensile strain at bottom of asphalt concrete [microstrain]
μe_v	= vertical compressive strain at top of subgrade [microstrain]
s_t	= horizontal tensile stress at bottom of CTB subbase [MPa]
f_t	= flexural tensile strength of CTB material [MPa].

Although the performance relationship for the CTB material [6] has been used at AAS for some time, a thorough laboratory investigation based on local materials had never taken place. As it showed that the design is very sensitive for the performance relationship of the CTB, a laboratory program [8] was executed to confirm its validity for the standard mix used by AAS based on 60% recycled concrete and 40% milled asphalt rubble. Slabs of 600x600x150 mm were made and used to saw beams of 600x100x100 mm and core 150 mm diameter specimen. The beams were used for the Four Point Bending (4PB) test set-up, whereas the cores were cut in half to be used for the Semi Circular Bending (SCB) test. As the determination of the mechanical characteristics based on the preparation of beams is very labor-intensive and expensive, the SCB procedure was chosen to confirm its usefulness in comparison with the 4PB. It takes less effort to obtain SCB sample from existing pavements and there is less damage to be repaired. Figure 1 shows the results of both tests in comparison with the fatigue model used up to now [6] based on a flexural tensile strength of 2.25 and 2.50 MPa. The laboratory test results show close correlation with the performance relationship for a flexural tensile strength of 3.00 MPa, as shown is Figure 1.

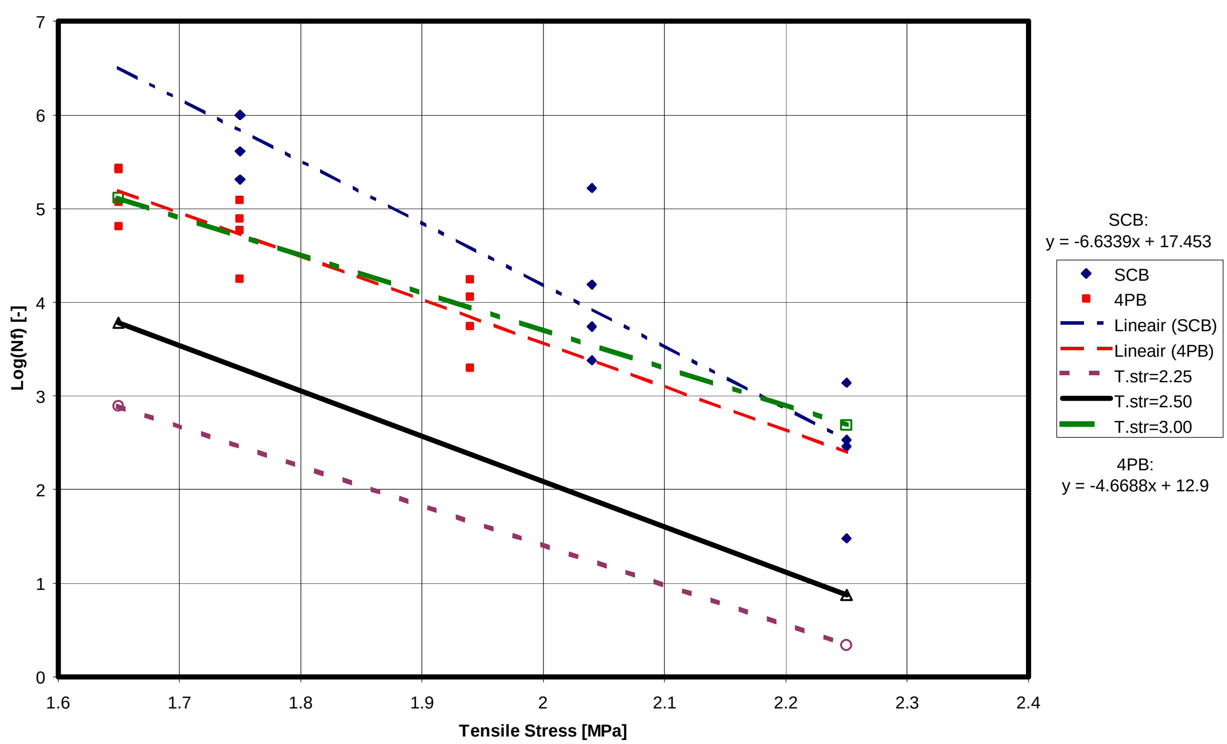

Figure 1. Comparison between laboratory results and performance relationship used

The model for the pavement structure at the start of the analysis is shown in Table 2.

Table 2. Model pavement structure

Model	Thickness [mm]	E-modulus [MPa]	Poisson Ratio [?]	Remarks
Asphalt concrete	variable	7,000	0.40	
Unbound base	200	800	0.35	
Bound subbase	variable	10,000	0.20	compressive strength 12.5 MPa
Subgrade	-	45	0.35	including 500 mm sand layer

The positive effect of the vacuum consolidation method on the subgrade strength has not been taken into account and can be considered as an extra factor of safety.

Structural analysis

The structural life of a pavement structure depends upon the number of aircraft movements on the heaviest loaded pavement lane. As the number of passing aircraft is made up out of a mix of different types with different gear arrangements, lateral wander has be taken into consideration. Apart from the NLA/A380 type of aircraft, the gear configurations of all other aircraft types in the mix are known. For this study the gear configuration of the NLA/A380 was based on the limited information available at the start of the study late 1998/beginning 1999 and is shown in Figure 2. At that time the NLA's were known as the B747-600X and A3XX. In the design the lay-out of the B747-600X was chosen.

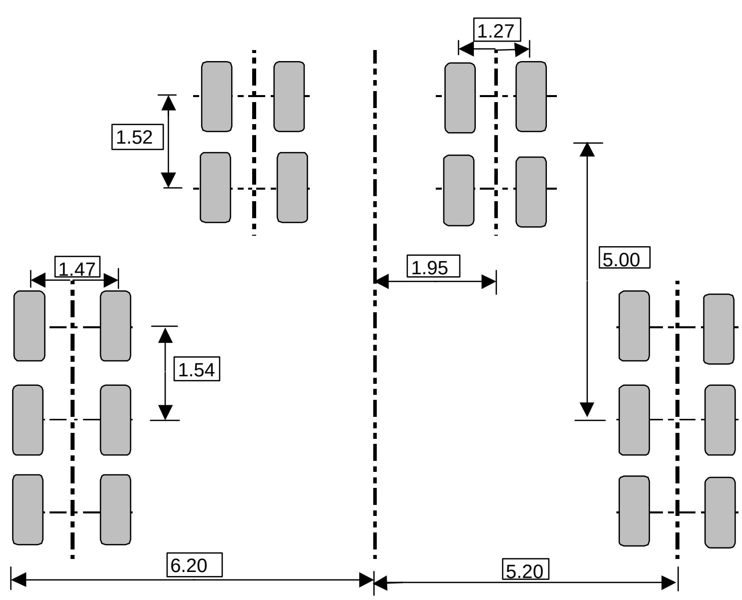

Figure 2. Adopted landing gear configuration NLA/A380 (not to scale)

The width of this transverse variation depends on:

- type of movement (take-off, landing, taxiing)
- type of pavement (runway, taxiway)
- width of pavement.

The APSDS (Airport Pavement Structural Design System) [9] has been used in the analysis process. The advantage of this software package is the use of the more realistic lateral wander concept based on the lateral distribution of stresses and strains instead of the Pass-to-Coverage method. These stresses and strains are calculated for all gear configurations of the fleet-mix. Based on the stresses or strains computed in a particular pavement layer, the total cumulative damage (CDF = Cumulative Damage Factor) is calculated using Miner's well-known rule defined as the sum of the number of load repetitions (n_i) divided by the allowable number of load repetitions (N_i). Using APSDS the optimum thickness can be calculated automatically for a given layer using the CDF procedure. In this way the pavement structure has been optimized based on the performance relationships for AC, CTB and subgrade. The concept of the alternative pavement design was to have the critical design criterion positioned at the bottom of the asphalt layer. In this way corrective measures needed to increase the design life can be achieved in a minimum time frame. The analysis shows that this can be achieved with the proposed alternative design. Figure 3 shows the results of the APSDS output based on the critical asphalt strain criterion. In the legend the type of movement is linked to the aircraft type notation, L is landing and T is take-off.

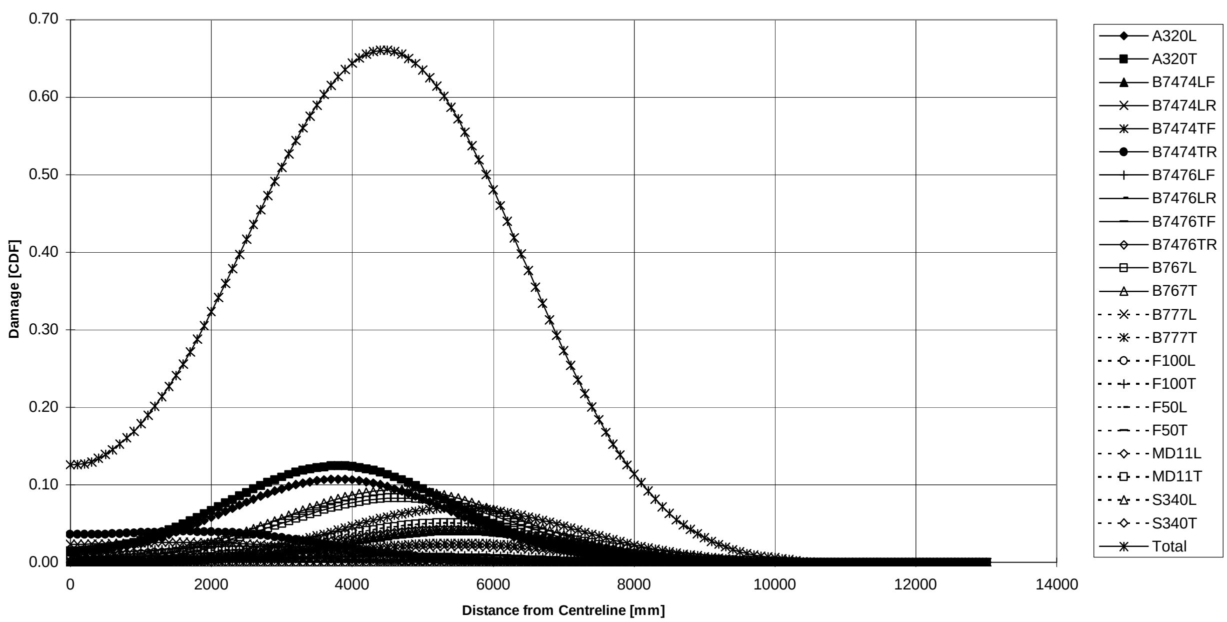

Figure 3. CDF analysis result asphalt strain criterion

The CDF based on the asphalt strain is 0.66 and is more or less equally influenced by all types of aircraft, although the influence of the less heavy A320 is more pronounced through its higher frequency. The result of the same analysis for the CTB subbase layer is shown in Figure 4.

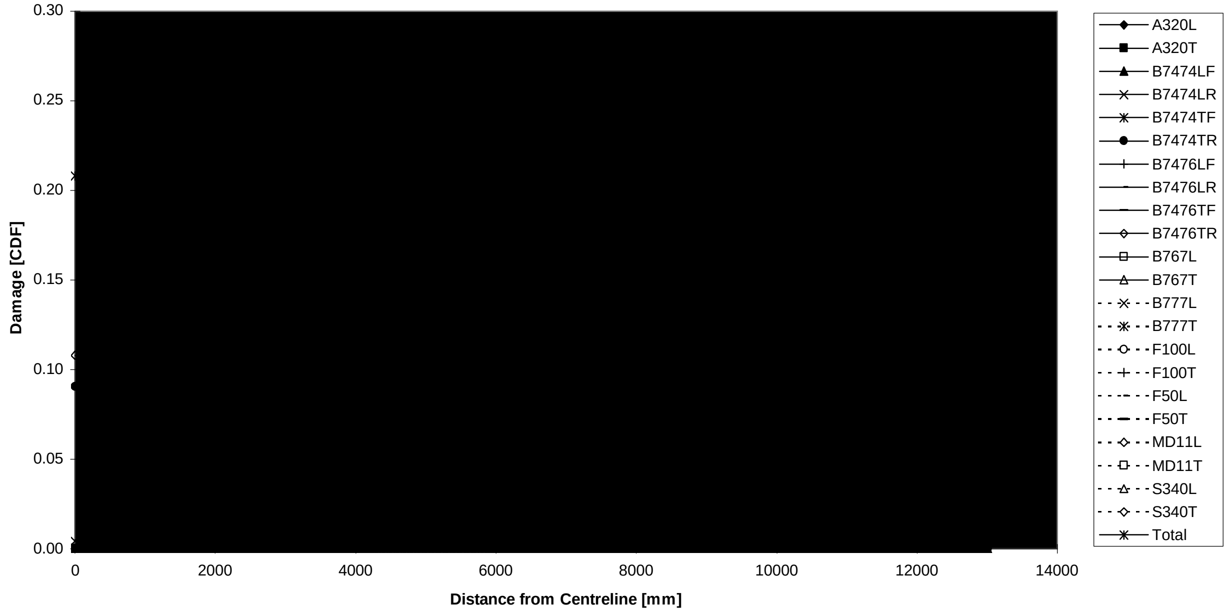

Figure 4. CDF analysis result CTB criterion

The CDF based on the CTB stress criterion is 0.25 for a material with an E-modulus of 10,000 MPa and a flexural tensile strength of 2.5 MPa. This seemingly safe CDF is however very sensitive for variations in mechanical characteristics. A 10% lower flexural strength will increase the CDF to 1.05, which means that structural cracking could take place. Figure 2 also shows very clearly that, in contrast to the AC layer, the maximum tensile stress mainly depends on the four heaviest aircraft types at their maximum take-off weight (MTOW).

Large quantities of asphalt and concrete rubble are the result of extensive reconstruction having taken place and it is standard practice for AAS to recycle these materials into the new pavements being constructed. A mix of 60% concrete and 40% asphalt rubble is the standard for all CTB layers. Due to variations in strength of each particle, inherent to the recycling process, a 10% variation in flexural strength is very likely to be present and the low subgrade strength can even increase the in-situ strength variation. This variation, together with the sensitivity of cement bound materials to frequency and weight of loading as well as the development of the ultra-heavy new generation NLA types, was the motive to look for the alternative design as proposed.

The ‘standard’ structure based on a 700 mm thick CTB base layer has a CDF of 0.96 for a tensile strength of 2.25 MPa. In case the A380 movements are twice as many as predicted the CDF is increasing to 1.55, causing structural failure of the CTB base layer. For this reason the alternative structure has been recalculated based on the development of cracks, reducing the E-modulus to a value of 5,000 MPa, resulting in an AC CDF of 0.92. To avoid random cracking and control the possible reduction in E-modulus the CTB subbase, dummy joints are sawed into the surface at a grid of 3.5 x 3.5 meter. Aggregate interlock in the dummy joints, together with the controlled cracking procedure, will keep the E-modulus at an acceptable high level during its service life.

Comparison with LEDFAA

The introduction of the A380 necessitate airports to make allowance for this new heavy type of aircraft in their maintenance, rehabilitation and reconstruction programs during the coming years. A design method incorporating these types of NLA aircraft does not exist yet, which has led to the use of a mechanistic analytical design based on the APSDS approach. For a relative comparison the computer based LEDFAA method has been used, although this method has been introduced only to cope with the tridem landing gears of the B777. On the one hand the design principles of LEDFAA have been followed, on the other hand the APSDS procedures have been followed as closely as possible.

For the design load the fleet-mix of landing aircraft as well as aircraft taking-off has been used, unlike the recommended use of departing aircraft only in LEDFAA. As new aircraft types cannot be added to the Aircraft Library, the A380 has been configured based on the maximum possible Gross Weight of a B747-400. The still existing differences in Gross Weight and tridem lay-out have been converted into an increase in frequency based on the conversion equation used in [2] Chapter 305.

For configuring the alternative pavement structure an ‘undefined’ layer has been added to represent the high quality crushed aggregate unbound material. As it is common practice in the Netherlands to use a high modulus asphalt concrete throughout all the bituminous bound material, a combination of a P-401 AC Surface and a stabilized P-401 Asphalt has been used. The bound subbase layer is represented by the stabilized P-304 CTB material. The calculated thickness based on APSDS has been compared with the required thickness based on LEDFAA, together with a ‘standard’ FAA flexible design. The results of this comparison are shown in Figure 5.

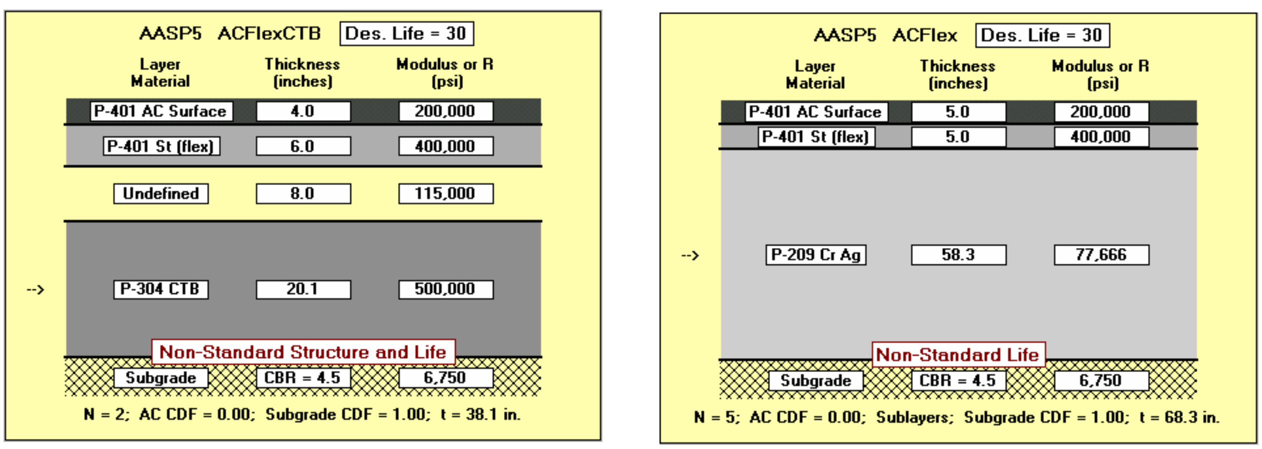

Figure 5. Thickness comparison between proposed alternative and flexible solution

Based on the CDF LEDFAA procedure the required 38.1 inch alternative structure in the left part of Figure 5 agrees with the 950 mm APSDS requirement. The flexible solution including a stabilized P-401 Asphalt base layer requires a thickness of 68.3 in. (1735 mm) based on the heavy A380 loading and 30 years design life. The flexible solution underlines the point of view that it is undesirable that an increase in Gross Weight of aircraft results in an excessive pavement thickness for low strength subgrades. The thought-out use of a cement bound subbase layer for stiffness and load spreading capabilities can be cost effective and the exchange of the CTB layer by a P-306 Econocrete subbase results in another 2.5 in. reduction in required thickness.

In contrast to the APSDS design the LEDFAA calculations report that the subgrade CDF seems to be the design criterion most of the times. Based on the load spreading capabilities of the bound subbase layer of the alternative structure this does not seem to be realistic. In principle it is undesirable to have the subgrade determining the design as this can result in secondary deformation in case of overloading at a location difficult to get under control once it occurs. For the same reason thick unbound aggregate layers are not recommended as measure for increasing the structural strength of pavements to be built for the new generation heavy aircraft.

Behavior of unbound aggregate interlayer

The use of unbound granular material is common practice for many airfield pavements, however the implementation of fundamental design criteria is not a standard procedure. The main concern is permanent deformation under the heavy wheel loads of the NLA type of aircraft influenced by the non-linear behavior in combination with stress dependency. In the past early failures have been reported due to water trapped in this unbound layer. The use of high quality crushed aggregates with good drainage characteristics and extra drainage measures will prevent water being trapped in this layer. An analysis of the behavior of unbound crushed Basalt under a wheel load of an A380 was carried out based on its stress dependent characteristics. The material parameters needed to analyze the permanent deformation behavior are determined in a laboratory investigation by use of cyclic triaxial testing [10]. The triaxial cell used has a diameter of 300 mm and a height of 600 mm. The stress dependent resilient modulus M_r is most commonly described by the M_r-? model:

- $$M_r = k_1 \left(\frac{q}{q_o} \right)^{k_2} \qquad (4)$$

The sum of the principal stresses (θ) is:

- $$q = s_1 + s_2 + s_3 \qquad (5)$$

where:

M_r	= resilient modulus [MPa]
θ	= sum of principal stresses [kPa]
θ_0	= reference stress for θ = 0 kPa
$\sigma_{1,3}$	= principal stresses [kPa]
k_1	= model parameter [MPa]
k_2	= model parameter [-].

Research studies [11] did prove that M_r-? model calculations result in predictions showing close agreement with actual field monitoring results. The resulting parameters k_1 and k_2 for the Basalt material, based on the triaxial testing were found to be respectively 99.9 and 0.264.

The stress ratio $s_1/s_{1,f}$ (main principal stress/maximum allowable stress) is a measure for the sensitivity for failure of the material tested. This mechanism is based on the Mohr-Coulomb failure theory.

For the Basalt materials the angle of internal friction is 45.6^o and cohesion 90.5 kPa. These values are used for the calculation of the stress ratio $s_1/s_{1,f}$ over the thickness of the unbound aggregate layer and graphical presented in Figure 6.

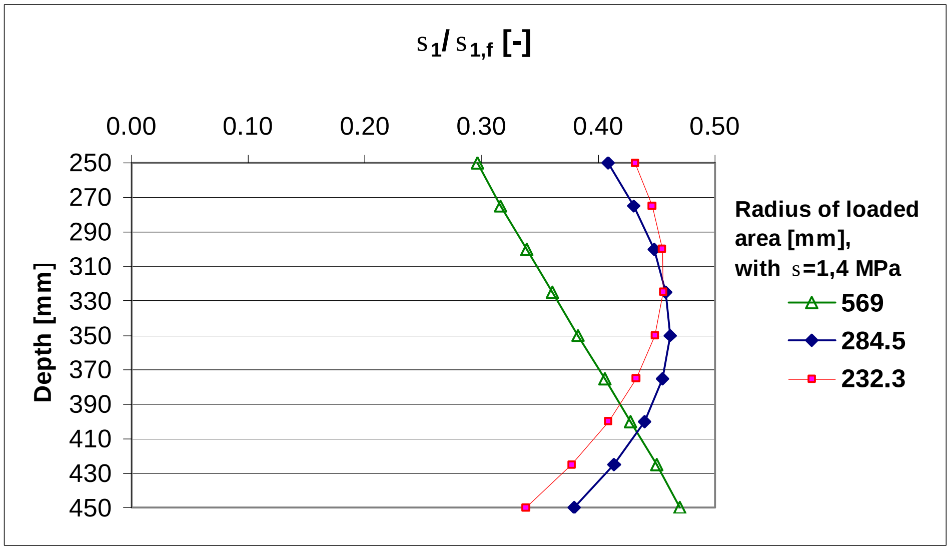

Figure 6. Stress ratio versus depth

The predicted stress ratios have been compared with the behavior of the Basalt aggregate under the triaxial loading, in which the development of permanent strain is related to the number of load repetitions (Figure 7).

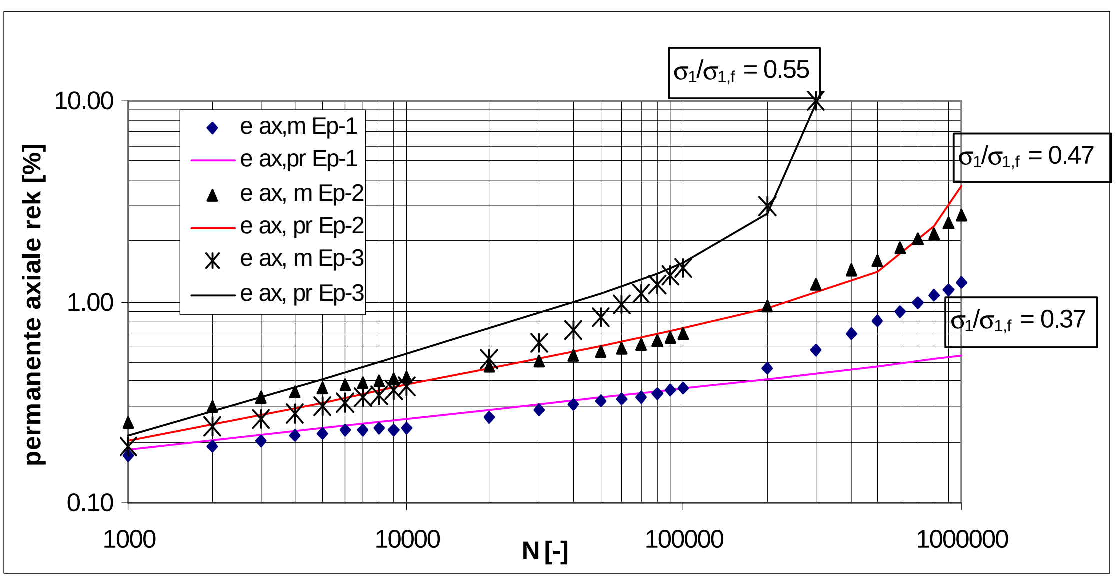

Figure 7. Development of permanent strain in a Basalt aggregate

The proposed alternative design for the 5th runway was adopted for the reconstruction of taxiway A8-9. The design criteria for the stress ratio $s_1/s_{1,f}$ was calculated at 0.22 for 170,000 load repetitions of a MD11, being characteristic for this part of the Taxiway. Using Figure 8 the permanent strain is about 0.3%, resulting in a permanent deformation of 1.0 mm in a 200 mm thick Basalt subbase layer.

Conclusions

On the basis of the foregoing study and laboratory-testing program the following conclusions can be drawn:

- The current design standards (FAA, ICAO) for flexible airport pavements do not allow the implementation of new aircraft types and the use of alternative structures or materials.
- The mechanistic-analytical design program APSDS, based on layered elastic principles, is an extremely useful tool in handling a complex fleet-mix with actual landing gear configurations, as well as local available materials, without the need of oversimplification of the design inputs.
- The use of a load spreading CTB subbase layer in combination at soft subgrade locations will limit the need for unrealistic thick pavement structures and the increasing risk of permanent deformation due to the introduction of the New Large Aircraft types.
- Vacuum consolidation is a quick method for the realization of an accelerated settlement to minimize possible future total and differential settlements and associated runway roughness. The positive effects of this subgrade treatment through an increased strength has been used as a factor of safety.
- Airfield pavements should be designed in such a way as to ensure that other failure modes than the vertical subgrade strain should govern the design as damage due to overloading results in expansive maintenance measures and inadmissible operational consequences.
- More fundamental research is needed to predict the deformation behavior of unbound aggregate layers in combination with the monitoring of actual pavement structures in service.

Acknowledgement

This paper was prepared from a study performed for the Combination 5th Runway on behalf of Amsterdam Airport Schiphol, Business Unit Airlines. The content of this paper reflects the views of the author who is responsible for the facts and accuracy of the data presented. The content does not necessarily reflect the official views and policies of Amsterdam Airport Schiphol.

References

[1] International Civil Aviation Organisation (ICAO), *Aerodrome Design Manual, Part 3: Pavements*

[2] *Airport Pavement Design and Evaluation*, Federal Aviation Administration, Advisory Circular AC 150/5320-6D, 7/7/95

[3] *Airport Pavement Design for the Boeing 777 Airplane*, Federal Aviation Administration, Advisory Circular AC 150/5320-16, 10/22/95

[4] Drenth, K.P. *Alternative Design Study 5th Runway Amsterdam Airport Schiphol – Final Design Pavement Structures*, NPC Report 988328, Utrecht, 31 May 2000 (in Dutch)

[5] *Manual Design and Reconstruction System Asphalt Pavements CARE*, Dutch Highway Agency, January 1993

[6] Starr D. Kohn, ea. *Development of a Thickness Design Procedure for Stabilized Layers under Rigid Airfield Pavements*, 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 18-20, 1989

[7] *Austroads: Pavement Design – A Guide to the Structural Design of Road Pavements*, Sydney 1992 (latest revision November 1997)

[8] Den Herder, A.J. ea. *Mechanical Characterization Cement Bound Base Material Tender Specs 5P-3159.S/Specs CT3*, NPC Report 998130, Utrecht, 13 July 1999 (in Dutch)

[9] *APSDS 4 Airport Structural Design System*, User Manual, Mincad Systems Pty. Ltd, September 2000

[10] Van Emst, G. ea *Assessment of the suitability of a Basalt aggregate as unbound base material*, NPC/Delft University of Technology Report 7-00-200-29-M, Delft/Utrecht May 2000

[11] Huurman, M. *Permanent deformation in concrete block pavements*. Ph.D. dissertation, Delft University of technology, Delft, 1997